

Saturation behaviour and load-induced thickness change of woven glass fibre fabrics

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Summary. The stress-strain behaviour of woven and coated technical textiles for structural purposes is well known to be anisotropic, nonlinear and viscoelastic. Tensile tests with cyclic loads on woven structural fabrics show a saturating behaviour regarding the stress-strain characteristics. Permanent strains are well known to be considerable, particularly in the first load cycles. However, the increase of permanent strains reduces in the following load cycles until only negligible additional permanent strains are observed. In common experimental test practice for structural fabrics, three to five load cycles are applied in total. Results show, that the saturation process may be considered progressed at that point, but not yet finished. In general, elastic material behaviour could be adopted for material modelling in the framework of a numerical analysis when the saturation is finished by an acceptable tolerance. The present paper investigates, whether and when the saturation process is completely finished for a woven glass fibre fabric. For this purpose a specific experimental protocol was developed where longitudinal and transverse strains are considered in uniaxial tensile tests with multiple load cycles.

Furthermore, in order to reach beyond the state-of-the-art linear-elastic material model, a new nonlinear anisotropic hyperelastic material model formulated in a full three-dimensional continuum mechanics setup can be considered. That means, that a change in thickness due to axial loading may be taken into account. For this reason, a protocol was developed such that the thickness change is also measured in the saturation tests. The results from these investigations are presented and interpreted in the present paper.

1 INTRODUCTION

The stress-strain behaviour of woven fabrics is known to be anisotropic, nonlinear and inelastic in general, see Figure 1. But it is also well known that nonlinearity and permanent strain increments decrease from load cycle to load cycle, particularly in the first load cycles. In common experimental test practice linked to textile architecture, three to five repeated load cycles are used to stabilise the stiffness behaviour in uniaxial or – more typical – biaxial tensile tests aiming to derive stiffness parameters [1–4]. Only two investigations are known in which ten or twenty load cycles were examined [5, 6]. Therein, the longitudinal strain development of PVC-coated polyester fabric was analysed, but transverse strains were disregarded. Up to now, no studies with multiple load cycles are known for PTFE-coated glass fibre fabrics, besides PES-PVC the other mostly used material for textile architecture.

Moreover, the material's residual or permanent strain has to be considered in the compensation planning in order to ensure a certain safe level of prestress in the structural membrane. Altogether, it always seemed justified to presume elastic material behaviour for the structural analysis in the framework of a membrane structure's design verification. But, up to now, this presumption has never been thoroughly investigated and proven. Is the material behaviour really properly saturated after three or five load cycles?

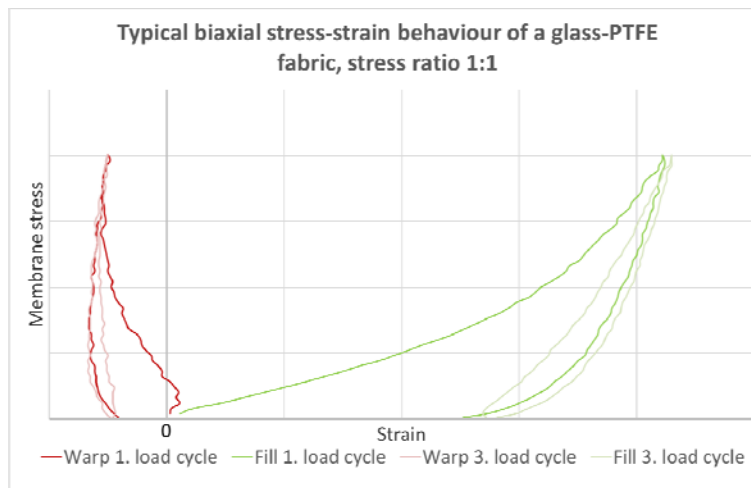


Figure 1: Typical stress-strain diagram for a glass-PTFE fabric under biaxial stress ratio warp:fill 1:1 showing nonlinearity, inelasticity and anisotropy

The first aim of this contribution is to investigate whether and when a woven glass-PTFE fabric saturates, i. e. gets into a stable state where the stiffness parameters do not vary significantly anymore from load cycle to load cycle. This state is also referred to as the “stable state of a woven fabric” in [3], there assumed to be reached within five load cycles with acceptable tolerance for practical applications.

The second aim is to investigate the load-induced change in thickness for the investigated glass fibre fabric. For the currently used plane-stress linear-elastic constitutive model, a change in thickness is not considered. However, for the development of a new anisotropic polyconvex hyperelastic material model formulated in a full three-dimensional continuum

mechanics setup in the sense of [7, 8], knowledge about this physical property is required. Different methods for measuring the thickness of a coated fabric as well as results for thickness and load-induced thickness changes are presented and discussed.

2 MATERIALS AND METHODS

The investigated material is a PTFE-coated glass fibre fabric. Table 1 illustrates basic characteristics of the material as measured in the Essen Laboratory for Lightweight Structures (ELLF) at the University of Duisburg-Essen. Due to the measured tensile strength f_t it can be classified as type II according to the harmonised classification in [9], although it is quite near to a type III.

Uniaxial cyclic strip tensile tests were performed on the 20-kN biaxial test rig of the ELLF. The test setup is illustrated in Figure 2. The reason for using a biaxial test rig for uniaxial tests was the ability to measure in-plane transverse strain and to have enough space to realise thickness changes and surface roughness measurements during the tensile tests. Longitudinal and transverse strains in the membrane plane were detected optically by a camera system continuously tracking four markers in the measurement field.

Table 1: Characteristics of the investigated glass-PTFE-material

Property		Standard	Measured value	Unit
Tensile strength f_t Warp / Fill	Mean	DIN EN ISO 1421 – strip method	135.5 / 117.5	kN/m
	5%-fractile*		132.1 / 112.0	
Type**		according to [9]	II	-
Total weight		DIN EN ISO 2286-2	877	g/m ²
Thickness		DIN EN ISO 2286-3	0.57	mm
Weave		-	Plain weave 1/1	-
Yarn density Warp / Fill		DIN EN 1049	12.3 / 14.4	yarns/cm
Yarn size Warp / Fill		DIN EN ISO 2060	1360 / 1360***	dtex

* according to EN 1990 with a fractile factor $k_n = 2.33$

** according to proposed classification in [9] based on the measured tensile strength f_t

*** manufacturer information

Three tests with yarn-parallel warp strips and three tests with yarn-parallel fill strips were conducted for statistical reasons. The load rate was set to 1.0 kN/m/s. Additionally, one test in each fabric direction was scheduled with a load rate ten times lower, i. e. 0.1 kN/m/s, in order to check whether the load rate had an impact on the recorded data.

Fifty regular load cycles (LCs) have been performed in each test. The maximum test stress in each cycle was 25 % of the lower tensile strength $f_{t,min}$ given in the material data sheet: $\max \sigma = 116/4 = 29$ kN/m. Note that the notion of stress refers here to the stress resultant defined as the integral over the thickness. The chosen maximum test stress matches the typical

value obtained by applying a safety and strength reduction factor of four in the field of structural membrane constructions. The minimum test stress in each cycle was zero. In order to ensure that creep processes were completely finished before load cycle N° 50, a hold time of 30 minutes on the maximum test stress was scheduled in the 49th load cycle. After load cycle N° 50, another hold time of 60 min. on max σ was scheduled. This procedure was only chosen for providing time to perform thickness and roughness measurements with different methods. The complete load protocol is given in Figure 3.

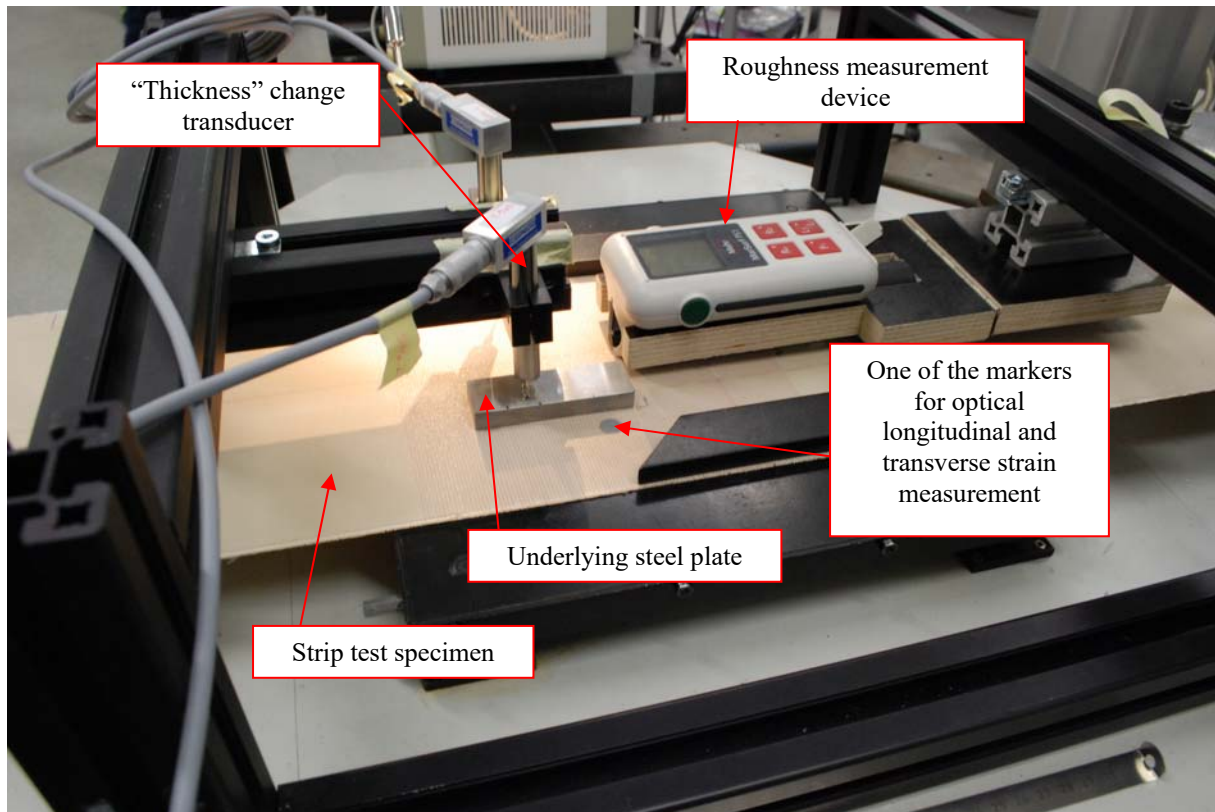


Figure 2: Test setup for the uniaxial cyclic tensile tests

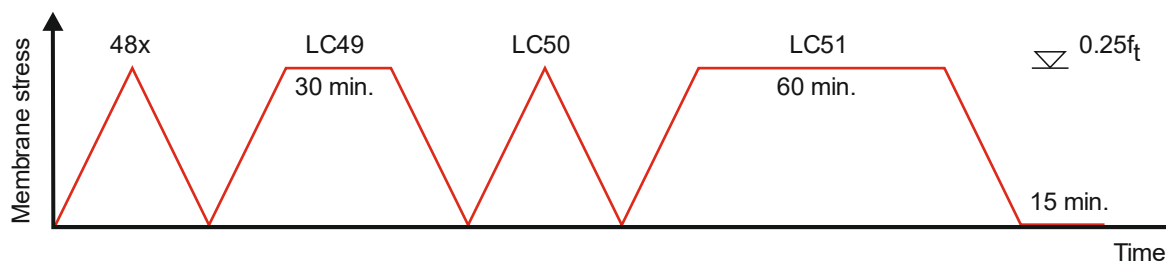


Figure 3: Load protocol of the uniaxial cyclic tensile tests

Preliminary studies on the thickness measurements with different measurement devices such as a thickness tester according to EN ISO 2286-3 [10], a digital calliper, a digital micrometer screw and a microscope as an optical method revealed that the result depends – partially heavily – on the chosen measurement device, see Table 2. This is assumed to be mainly due to different pressures normal to the membrane surface applied by the different devices. Apparently, the investigated material is quite sensitive to this impact. But also the different surface areas covered by the devices could possibly affect the results because single ridges on the surface are considerable higher than others.

Table 2: Different thickness measurement results obtained by different measurement methods for one and the same test sample piece

Measurement device / method	Mean thickness* [mm]
Thickness tester acc. to DIN EN ISO 2286-3	0.53
Digital calliper	0.52
Digital micrometer screw	0.50
Evaluation of microscopic cross section	0.52
Displacement transducer with underlying steel plate	0.54

* Mean of four single measurements per method, rounded to two decimal places.

For future considerations of the thickness and thickness change in a 3D material model an extensive, reproducible and non-invasive measurement method is required. Finally, it was decided to measure the thickness of the virgin material with the same method as developed for detecting the thickness change: a displacement transducer normal to the membrane surface with a steel plate lying between the transducer and the membrane surface, see Figure 4. The steel plate's surfaces are smoothed. To avoid any significant bending of the steel plate under the spring force of the transducer, the thickness of the steel plate is chosen to $t = 10$ mm while the length and width of the steel plate were $l = 75$ mm and $b = 25$ mm. Of all compared mechanical thickness measurement methods, the transducer with steel plate underlayment led to the highest values, see Table 2. This indicates that this method is least affecting the measurement. If – for simplification reasons – a constant distribution is assumed, the stress between the steel plate and the membrane caused by the dead load of the steel plate and the transducer spring force becomes only 0.0009 N/mm^2 , calculated with a given spring constant of $D = 0.056 \text{ N/mm}$ according to the producer's data and an initial displacement of the spring of 4.5 mm. As a comparison: the stress due to the standardised thickness measurement according to EN ISO 2286-3 is ten times higher! Moreover, the transducer-steel plate combination covers the greatest area and spans from peak to peak in this area, see also Figure 4. Both features combined, increases the probability to cover peaks and leads to larger values. On the contrary, the more locally working measuring devices as thickness tester, calliper and micrometer screw (listed in order of increasing “locality”) – and also the evaluation of microscopic cross sections – have a lower probability to cover the highest peaks.

In order to ensure a high quality of the thickness change measurement with the transducer-steel plate combination, the planar position of the steel plate within the test setup was checked before each test in the individual setup.

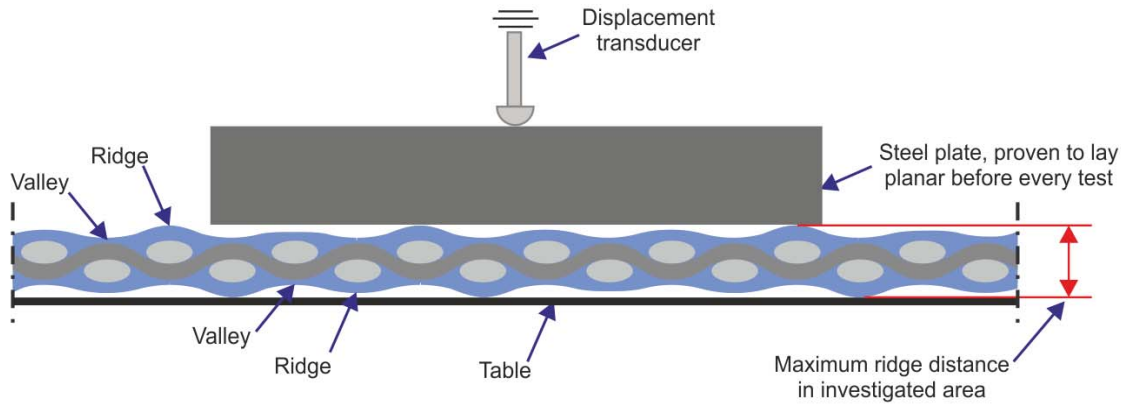


Figure 4: Measurement of thickness and thickness change: displacement transducer with a steel plate lying between transducer and membrane surface (not drawn to scale)

In fact, the ridge heights deviate. This is indicated in Figure 4. The chosen measurement method actually detects the membrane’s “maximum ridge distance” in the area which is covered by the steel plate. This is in principle very similar to all other mechanical methods described above: they all measure the maximum thickness in the area covered by the measurement device – disregarding that they might reduce the maximum by compressing particularly the highest ridges.

During the cyclic tensile tests, the change of the ridge distance was continuously recorded with the transducer-steel plate combination. Additionally, the surface topography of the membrane was measured before and in the final phase of the tests under full load with a roughness measurement device within a range of 17.5 mm, see Figure 2. The surface roughness results are not presented in this paper.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 General

Longitudinal and in-plane transverse strains were directly recorded by the optical measurement system of the biaxial test rig. The thickness change was externally recorded as the ridge distance change by the displacement transducer with underlying steel plate. The results of the strip tests with stress in warp and fill direction are presented and discussed in this section. The interpretation focusses on whether and when the stress-strain behaviour saturates, i. e. becomes elastic. As main indicators, the elastic moduli in form of the secant moduli and in-plane Poisson’s ratios are calculated for each load cycle separately.

3.2 Longitudinal and transverse strain in the membrane plane

Figure 5 shows the results of all three “fast” tests and the one “slow” test in warp direction as strain versus time diagrams until the end of the 50th load cycle. In general, the deviations over all tests are low. Even the test with low stress rate does not result in significantly different strain values. Looking only on the transverse strains, the first fast test appears to be an outlier with much lower absolute strain values than the other test specimens. The turning points of longitudinal strains (minimal and maximal value in each cycle) saturate apparently after ca. ten load cycles at a strain level of approximately $\varepsilon = 1.9\%$. Then, the permanent strains have also saturated. During the hold time in the 49th load cycle, creep strain is negligible.

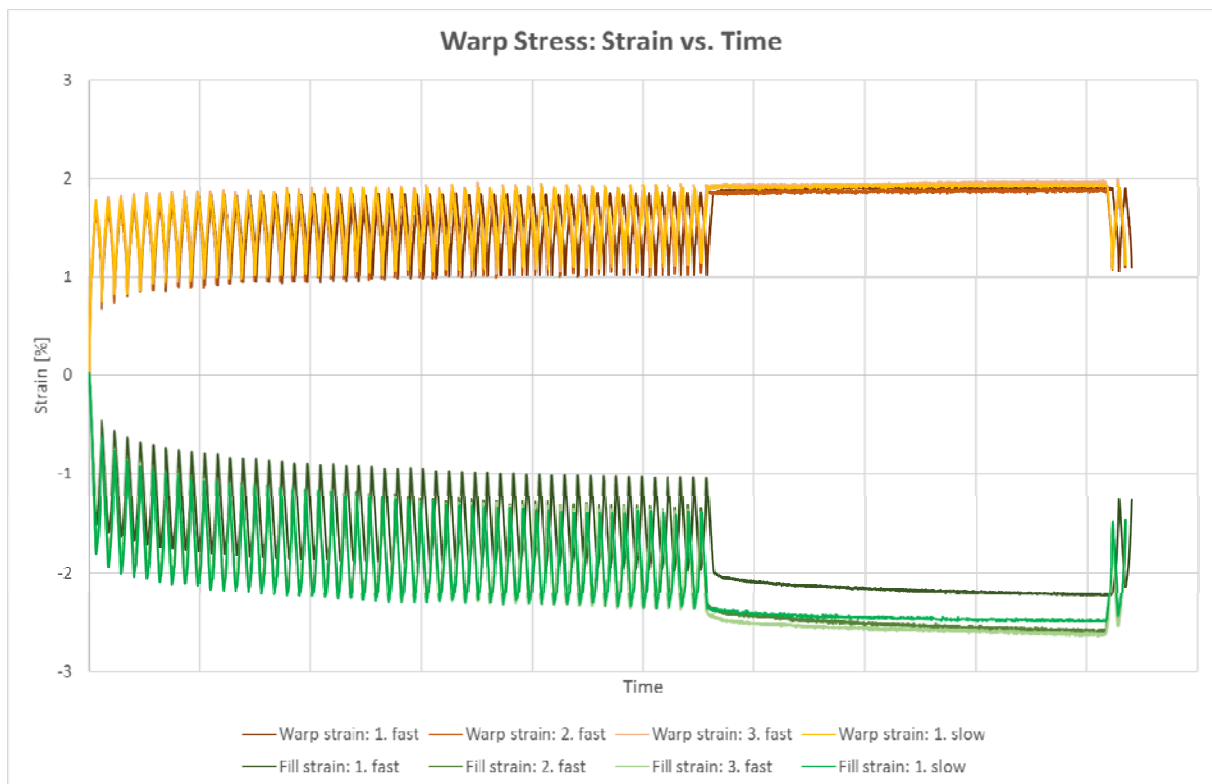


Figure 5: Longitudinal strain and transverse strain in membrane plane vs. time for all cyclic tensile tests in warp direction (timeline of the slow test compressed for comparability reasons)

However, transverse strain does not seem to saturate at all. Even after 48 load cycles with full design stress a clearly visible growth of strain is observed. Additionally, creep strain during the hold time is increasing constantly. After 30 minutes, a growth of ca. 10 % strain relating to the beginning of the hold time is observed and still the strain-time curves show no evidence to converge. Surprisingly, this happens while at the same time no creep is detected in longitudinal direction.

The recorded data appear to be independent of the stress rate. Remarkable is that the transverse strains are greater than the longitudinal strains, although this is known to be typical

for glass fibre fabrics!

Figure 6 shows the results of all three “fast” tests and the one “slow” test in fill direction as strain versus time diagrams, again until the end of the 50th load cycle. Due to the complex test setup, the camera temporarily lost two markers in the 3rd fast and in the slow test. This is marked in Figure 6. These failures could be fixed within a short time so that the rest of the test delivered reliable data.

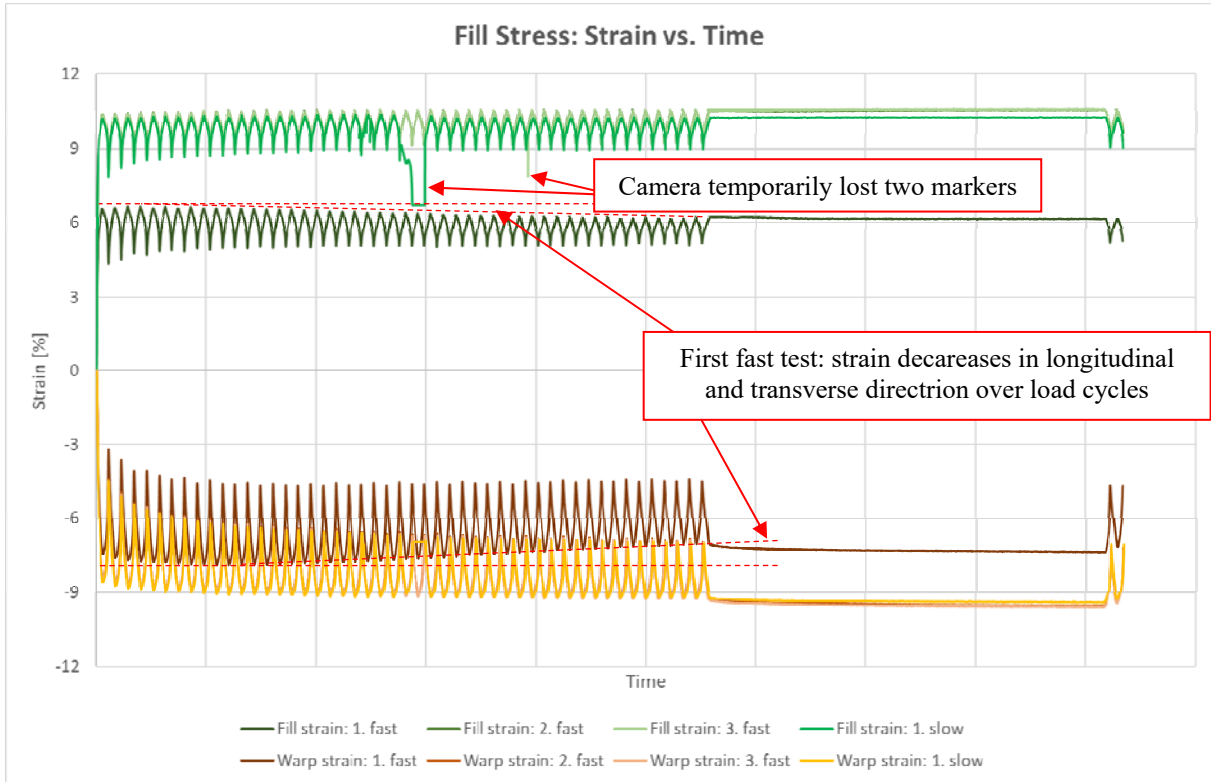


Figure 6: Longitudinal strain and transverse strain in membrane plane vs. time for all cyclic tensile tests in fill direction (timeline of the slow test compressed for comparability reasons)

The first fast test shows a very different behaviour than all the others: the absolute strain magnitudes are considerable smaller in general and even decrease over time. All other test specimens responded very similar to each other so that single curves appear to be invisible in the diagram. Saturation is observed after approximately ten load cycles. The maximum and minimum strain values are constant afterwards for all load cycles and even during the hold time in the 49th load cycle. That means, all creep is removed in the load cycles before. As for the warp tests, there is no significant difference observed between the high and low stress rates. During fill stressing, the transverse strains are smaller than the longitudinal strains – except for the first fast test.

In order to investigate whether elastic parameters saturate in the same manner as the strain values, two linear-elastic parameters are derived for each load cycle i :

- the elastic modulus as secant modulus, calculated as the longitudinal strain increment $\Delta\epsilon_{L,i}$ over the stress increment $\Delta\sigma_i$ and

- Poisson's ratio as the negative transverse strain increment $\Delta\epsilon_{T,i}$ over the longitudinal strain increment $\Delta\epsilon_{L,i}$.

For example, the determination of the elastic moduli is indicated for fill direction in Figure 7. It can be recognised that nonlinearity decreases over the load cycles. The results for the elastic moduli and the Poisson's ratios are illustrated in Figure 8.

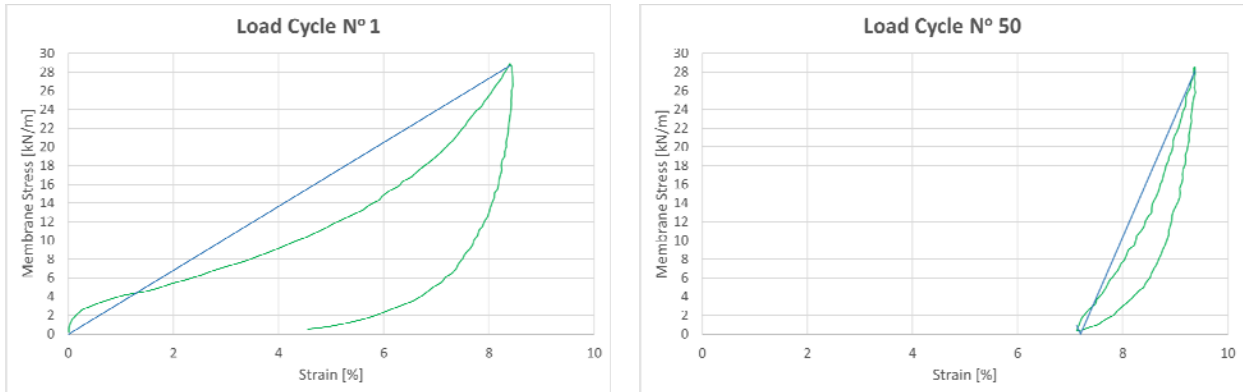


Figure 7: Determination of elastic moduli, exemplarily illustrated for fill direction in load cycle N° 1 (left) and load cycle N° 50 (right)

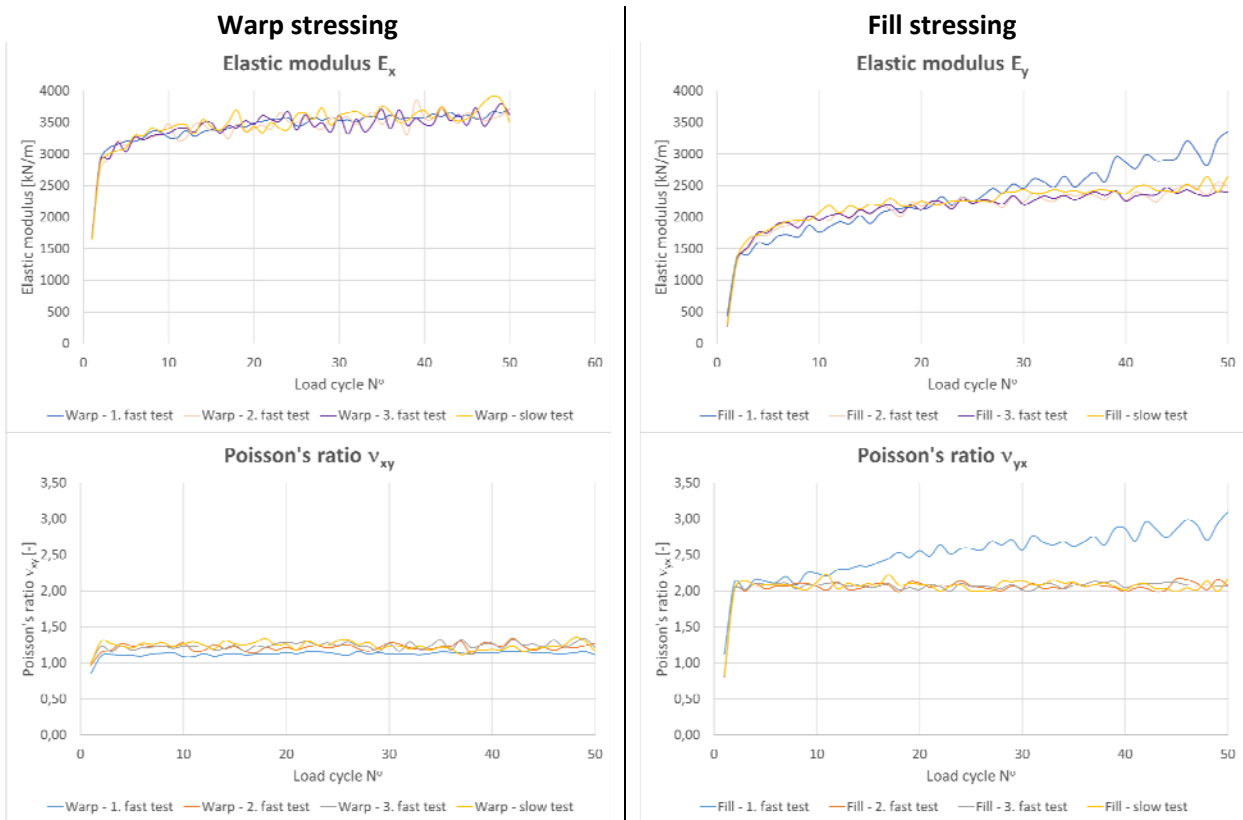


Figure 8: Saturation behaviour of elastic parameters

In fact, for warp stressing, the elastic moduli stabilise after ca. ten load cycles. Afterwards the increase yields to about 7 %, which has for sure a minor impact on analysis results. But for fill stressing, a further increase of about 30 % after load cycle N° 10 is observed – and the elastic moduli are still not saturated. This is surprising at first glance, because the strain peaks appeared to be saturated quite early in Figure 6. The reason for this behaviour can be found in the increasing permanent strains (minimal values of strains per cycle). This leads to decreasing strain increments for almost constant maximum strains.

Regarding the impact of the Poisson's ratio on membrane structural analyses, it can be stated that the observed variation over the load cycles of ca. $\Delta v = 0.1$ to $\Delta v = 0.2$ beyond load cycle N° 2 is insignificant for both warp and fill stressing.

3.3 Thickness or ridge distance change

The recorded thickness change in form of the ridge distance change during load cycling is illustrated in Figure 9. Usually an increase in the ridge distance is registered. Only the first fast test under warp stressing behaves completely different. It also starts with increasing thickness during increasing load, but later the measured data become unstructured. Due to that, this measurement is assessed erroneous. Another inaccuracy appears in the slow test under fill stressing. Several significant jumps can be recognised in the test data curve. In this test, several times helping weights had to be adjusted, which could have been enough interfering factors to disturb the measurement. This shows how sensitive the test equipment is. The absolute values should be handled with caution because oftentimes the change of the ridge distance becomes only a few micrometers during later load cycles, a magnitude which lies within the measuring inaccuracy of the transducer. Apart from that, values and trends were repeatable and thus appear to be reliable.

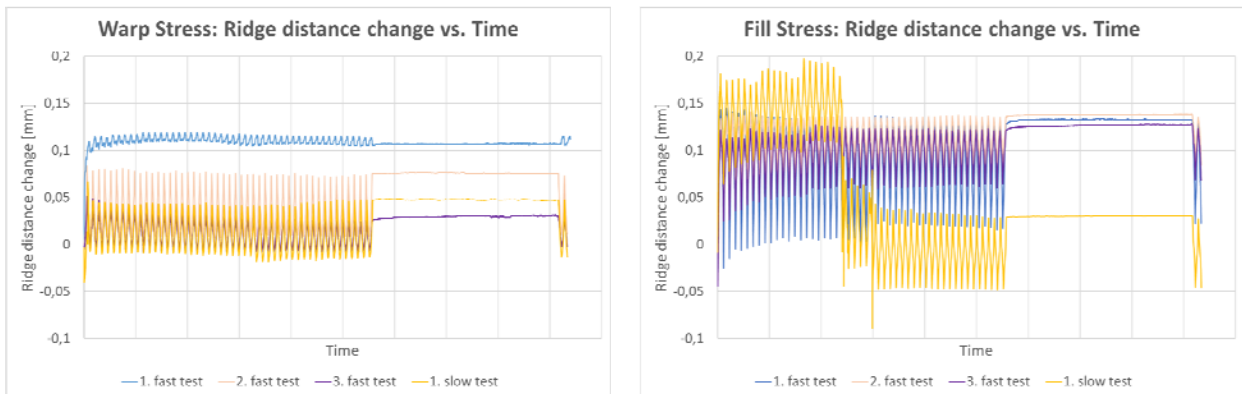


Figure 9: Recorded ridge distance change of all tests, under warp stressing (left) and under fill stressing (right)

In general, an increase of thickness is observed when stress raises. This effect is larger during fill stressing than during warp stressing. It is assumed that this effect is caused by the larger yarn crimp of the fill yarns: when they straighten under normal stress, they strongly force the warp yarns in new “height spots”.

With the initial thickness and the ridge distance change, the through-thickness strain and

the Poisson's ratio in through-thickness direction can be calculated, the latter one as the ratio of the through-thickness strain over the longitudinal strain increment in each load cycle. The resulting values are displayed in Figure 10. Poisson's ratios are negative because the material does not contract but expands in through-thickness direction.

The magnitude of thickness increase is relatively high. The thickness change was observed up to $\Delta t = 0.08$ mm under warp stressing and up to $\Delta t = 0.14$ mm under fill stressing in the single load cycles of the reliable tests. Related to an initial thickness in the beginning of the individual load cycles of approximately $t = 0.58$ mm to 0.66 mm, the strain in through-thickness direction becomes approximately 14 % during warp stressing and 30 % during fill stressing. This yields extreme Poisson's ratios in through-thickness direction of minimal approximately $v_{zx} = -15$ and $v_{zy} = -7$, respectively. The Poisson's ratio under fill stressing is considerably smaller due to higher longitudinal strains. Except for the slow test in warp direction, the through-thickness Poisson's ratios saturate for the reliable tests early, latest after approximately five load cycles.

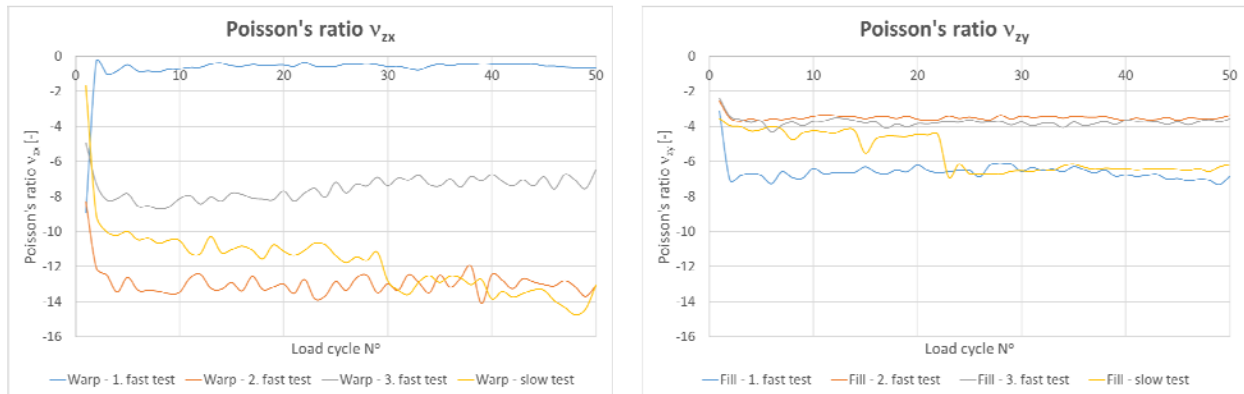


Figure 10: Poisson's ratios in through-thickness direction under warp stressing (left) and under fill stressing (right)

4 CONCLUSIONS

The application of an elastic material model requires an elastic material behaviour in acceptable tolerances. The aim of this contribution was to investigate for a structural glass-PTFE fabric whether and when stiffness properties saturate under cyclic loading. Uniaxial cyclic tensile tests have been performed independently in warp and fill direction with 50 load cycles. Longitudinal and in-plane transverse strain were measured.

From a practical application's point of view, the elastic modulus in warp direction is saturated after approximately ten load cycles and both Poisson's ratios in membrane plane are saturated already in the second load cycle for the material investigated. On the contrary, the elastic modulus in fill direction continuously grows until the 50th load cycle.

In order to support the development of a new hyperelastic material model based on 3D continuums mechanics, additionally the thickness and load-induced thickness change of the fabric was measured in form of the ridge distance and change of the ridge distance during uniaxial cyclic tests. Different thickness measurement methods have been investigated and discussed. The thickness change was observed to values up to 0.08 mm under warp stressing

and up to 0.14 mm under fill stressing. This leads to extreme Poisson's ratios in through-thickness direction of approximately -15 and -7, respectively. The Poisson's ratios in through-thickness saturate early, latest after five load cycles. These results should be however interpreted with view to the precision of the transducer, which is in the order of magnitude of the measured ridge distance change.

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REFERENCES

- [1] pr EN 17117-1:2017, Rubber or plastics-coated fabrics – Mechanical test methods under biaxial stress states – Part 1: Tensile stiffness properties.
- [2] Membrane Structures Association of Japan, MSAJ/M-02-1995, Testing Method for Elastic Constants of Membrane Materials, 1995.
- [3] J. Uhlemann, *Elastic constants of architectural fabrics for design purposes*, Dissertation, Institute for Metal and Lightweight Structures, University of Duisburg-Essen, Shaker Verlag, Aachen, 2016.
- [4] R. Blum, H. Bögner and G. Némóz, *Testing Methods and standards*, European Design Guide for Tensile Surface Structures, B. Forster and M. Mollaert (Eds.), TensiNet Ass., Brussel, 2004, pp. 219–241.
- [5] H.-W. Reinhardt, *Ein- und zweiachsige Verformungs- und Festigkeitsuntersuchungen an einem beschichteten Gittergewebe*. Mitteilungen des SFB 64 No. 31/75. Stuttgart, 1975.
- [6] G. Rehm and R. Münsch, *Zum Spannungs-Dehnungs-Verhalten im Gebrauchslastbereich und zum Bruchverhalten von PVC-beschichteten Polyestergeweben*, 2. Internationales Symposium Weitgespannte Flächentragwerke: 1. Vorberichte zum Kolloquium, Stuttgart, 1979.
- [7] D. Balzani, P. Neff, J. Schröder, G.A. Holzapfel, *A polyconvex framework for soft biological tissues. Adjustment to experimental data*. International Journal of Solids and Structures, Vol. 43, 2006.
- [8] J. Schröder, D. Balzani, N. Stranghöner, J. Uhlemann, F. Gruttmann, K. Saxe, *Membranstrukturen mit nicht-linearem anisotropen Materialverhalten – Aspekte der Materialprüfung und der numerischen Simulation*, Der Bauingenieur, Vol. 86, 2011.
- [9] N. Stranghöner et al., *Prospect for European guidance for the Structural Design of Tensile Membrane Structures: Support to the implementation, harmonization and further development of the Eurocodes*, JRC Science and Policy Report, European Commission, Joint Research Centre, Editors: M. Mollaert, S. Dimova, A. Pinto, St. Denton, EUR 25400 EN, European Union, 2016.
- [10] EN ISO 2286-3:2016, Rubber- or plastics-coated fabrics – Determination of roll characteristics – Part 3: Method for determination of thickness.